DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY

J. W. POWELL DIRECTOR

CONTRIBUTIONS

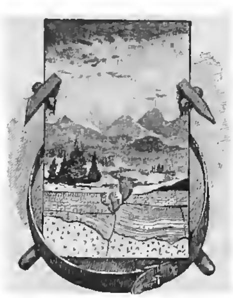
TO THE

HISTORY OF LAKE BONNEVILLE

BY

G. K. GILBERT

EXTRACT FROM THE ANNUAL REPORT OF THE DIRECTOR OF THE U. S. GEOLOGICAL SURVEY—1880-81



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I. INTRODUCTION.

In the organization of the Geological Survey by Mr. King, the territory subject to its operation was apportioned in a number of divisions. To each division a scientific corps was assigned, and in order that the labors and results of each corps might be characterized in the highest practicable degree by unity each geographic district was made to correspond to a great geologic province. The Division of the Great Basin is a province characterized by numerous small mountain ranges, and is thereby distinguished from its western neighbor, the Division of the Pacific, which contains a comparatively great mountain chain, the Sierra Nevada, and from its eastern neighbor, the Division of the Colorado, which includes as its chief feature the great group of plateaus of the Colorado Basin. At the north it is limited by the British Possessions, and at the south by the Mexican boundary, and it has an extent nearly twice as great as the Eastern and Middle States combined. Nearly the whole of this area is studded by mountain ridges, which are approximately parallel and have a meridional trend. None of them are of great height nor of great extent, and they are so numerous that many have no individual names known to the whites. Between them lie valleys filled by the alluvium that in past ages has been worn from their summits and sides, and in a few districts these valleys grow broad and blend together so as to constitute plains of some extent. The rainfall of the region is scant and the streams are few and small. Two great rivers traverse it, but their sources are beyond its limits. The Columbia, fed by the abundant precipitation of the uplands rising to the eastward, crosses in a northwest direction to the Pacific Ocean; the Colorado, rising in the same uplands, flows southward and westward to the Gulf of California. From the arid tract they receive a few small affluents, but except for the avenues opened by their waters it is scarcely probable that any streams rising within the district would find their way to the ocean. In the interval between the drainage basins of the two rivers there is a large district which gives rise to no outflowing streams, but returns to the air by evaporation all the moisture received from it as rain. It is

this district of continental drainage to which the title "Great Basin" is specifically applied, and it is from it that the Division receives its name. The geological survey of the Division involves the study of a wide range of topics. Not only does each mountain consist of a variety of geologic strata and embody a history of its own, but the district as a whole contains every great known group of formations, and their study cannot be conducted without a coincident study of the greater dynamic problems of geologic science. The Archæan, the Paleozoic, the Mesozoic, and the Tertiary systems are each developed in so many localities that no one of them can be studied fully without traversing a large portion of the entire area. Volcanic rocks abound in all parts, and phenomena pertinent to the study of the growth of mountains and the decay of mountains are everywhere present.

With the limited means at the disposal of the Survey it was manifestly impossible to occupy the entire field at once and carry on the work in a way that would be both geologically and geographically symmetric. It was necessary to restrict attention, and the question arose whether this should be done by selecting a limited district for initial work and beginning in it the study of every topic to which it might contribute, or by choosing a specific line of inquiry and carrying it through the entire area. The latter course was decided on, and the theme of study selected was the Quaternary history of the valleys of the Great Basin. It was already known that many of these valleys which are now destitute or nearly destitute of water, had contained, at a period of time geologically very late, a series of lakes, some of which were salt and some fresh; and it had been more than surmised that these lakes were the contemporaries of the glaciers of the Ice Epoch. The study of their history was therefore nearly identical with the study of the Quaternary history of the valleys, and it was to them that attention was chiefly directed.

The lowlands of the Great Basin are valleys without drainage to the ocean, and when the climate of the Glacial Epoch gave them a more generous supply of moisture the surplus was accumulated in their lower parts in quantities which bore a definite relation to the climate. When for centuries the climate became more humid the lakes rose and encroached upon the land, and when the reverse was true and aridity prevailed they dried away and the land was laid bare. The extent of the lakes was therefore the measure of the climate, and if we can rightly interpret the traces the lake margins have left of their successive positions we shall be furnished with a detailed history of the oscillations of climate in this region of the earth during that epoch. The problem of Glacial climate is one of the most interesting which now claims the attention of geologists, and if these Quaternary lakes can afford an independent history of the climatal changes by which the accumulations of ice were made and dissipated, they will make a most acceptable contribution to the subject.

Closely interwoven with the history of the oscillations of the water is the history of the sediments deposited by it, and the general study cannot be carried forward without at the same time investigating the conditions of sedimentation in inland seas. It is therefore hoped that the progress of the investigation will add something to our means of distinguishing, among the older geologic formations, strata which were formed under similar conditions, and will thus enable us to read more clearly some of the earlier pages of the geologic record which are now obscure.

Another collateral subject of investigation is the process of shore formation—the process, that is, by which the waves of a lake modify the configuration of the land upon which they break, and produce the peculiar topographic features characteristic of shores. This study has already been successfully pursued by others on the margins of existing bodies of water, but there are some details in the anatomy of shores which are necessarily concealed by living bodies of water, and can only be revealed by the dissection of the denuded remains of dead lakes.

The desiccation of the old lakes caused the concentration of their mineral contents, so that all of them which survive with diminished area are saline, and the positions of those which have entirely disappeared are marked by deposits of salt and other soluble minerals. The study of the Quaternary lakes is therefore inseparable from the study of the modern salines, and it may reasonably be anticipated that the final discussion of the results will throw new light upon the saliferous deposits of the older rocks.

At the time of the organization of the Survey it chanced that there was in the possession of the writer a considerable body of unpublished material bearing upon Lake Bonneville, and that lake was therefore selected as the first individual subject of study. Its investigation in the field has now been completed, and a full account of its history, so far as it has been found practicable to deduce it, is in preparation. But while this history will be monographic as regards Lake Bonneville, it will in another sense be only one of a series—to be followed in time by similar accounts of other Quaternary lakes, and eventually by general discussions of the various collateral topics developed by the investigation.

In the present paper it is proposed to give in brief the principal results of the year's work, reserving for the monograph the full presentation of the facts from which they are derived. They will be prefaced, however, by an outline of the subject as previously known, for the literature of Lake Bonneville is so scattered that a general familiarity with it cannot be assumed.

Whoever makes a careful examination of a tract of sea coast, first before a great storm and again after the storm has passed, cannot fail to discover various modifications wrought by the storm in the form or character of the coast. Wherever the water margin is overlooked by

a cliff it will be found that some portion of the rock or earth of the cliff has been washed away, and probably that fragments great or small have fallen from above. Wherever the shore is constituted by a beach or spit it will be found that additions have somewhere been made to the sand or shingle, and possibly that at other points losses have been sustained. It is universally recognized that these changes are the result of the conjoined action of waves and currents set in motion by the storm, and that they are limited to the immediate vicinity of the shore and to shallow water. There is a horizontal zone of activity practically corresponding with the zone which receives the force of the breakers, but extending somewhat farther downward, and along this zone nearly every portion of the coast either suffers abrasion or else grows by additions to its banks and bars. Where the coast is abraded, the zone of wave beating is carried progressively landward, and two features are wrought: the paring away of the land leaves a fringing terrace or shelf just beneath the water; and the same excavation produces a cliff at the landward margin of the terrace. Where the coast grows, its banks and bars are not merely enlarged, but if they did not before exist they are created. The sea-cliff and the terrace at its foot are the creatures of the wave and mark the spot where the nature of its action is destructive. The spit, the beach, and the bar are equally the creatures of the wave, and testify to its constructive energy.

In this way there arises a special topography of coasts, and when the waters of a sea or lake recede or disappear, the topographic features which were wrought by the waves survive, constituting a conspicuous and almost unmistakable record. Every element of this record is characterized by horizontality; the landward edge of the wave-cut terrace is a horizontal line coincident with the level base of the sea-cliff; the beach and the spit and all other constructive works are level-topped, having been built upward to a limit regulated by the force of the storm waves. When, therefore, one views a slope from which an ancient lake has been withdrawn he recognizes its shore trace in a series of features which embody a horizontal line. Here the line is the meeting of a terrace and a cliff, there it is the crest of an embankment, and elsewhere it is the brow of a delta plain; its manifestations are diverse, but it is never wanting. To an eye placed at the proper height and distance all its elements blend together and it stands forth as a continuous, horizontal, indubitable *shoreline.*

It is by records of this character that Lake Bonneville is chiefly known. All about the great basin of Utah the lower slopes of the mountains are skirted by these level tracings—not a single line merely at a single level, but a series of lines at many levels, testifying to a system of oscillations of an ancient lake.

The highest water line is 1,000 feet above the level of Great Salt Lake, and over every foot of the intervening profile can be traced evidence of the action of waves. There is, however, a great inequality of the record,

RESERVOIR BUTTE, SHOWING TERRACES OF THE BONNEVILLE SHORELINES.

and the most casual observation shows that the water lingered much longer at some stages than at others. One of the most conspicuous water lines is the highest of all, but its prominence is largely due to the fact that it marks the limit between the wave-wrought surface below and the rain-sculptured forms which rise above. Of the lower lines there is one lying about 400 feet below the highest, which is far more conspicuous than any other and has for this reason been given a special name—the Provo shoreline. The highest is distinctively known as the Bonneville shoreline. Between the Bonneville and the Provo four or five prominent lines can usually be seen, to which no individual names have been given, and it will be convenient to call these in this place the Intermediate shorelines. On the slopes below the Provo shore the water lines are less conspicuously drawn, and only a single one is so accentuated as to have been identified at numerous localities.

A lake without outlet cannot maintain a constant level, because its quantity of water depends upon the relation of the rainfall to the superficial evaporation, and these elements of climate are notoriously variable. A series of moist seasons increases its contents and causes its margin to advance upon the land, while a succession of dry seasons produces the reverse effect and makes it shrink from its borders. With a lake having a discharge the case is different, for every increase or diminution of supply, by slightly raising or lowering the surface, increases or diminishes the discharge, and thus a practical equilibrium is maintained. It can therefore rarely happen that the waters of a lake without outlet are held at one level for the time necessary to produce a strongly marked, individual shoreline, and for this reason it was early surmised that Lake Bonneville found an escape for its surplus waters at the times of the formation of the Bonneville and Provo shorelines. Search was therefore made for a point of outlet, and eventually it was discovered at the northern extremity of Cache Valley. The sill over which the water at first discharged was of soft material which yielded easily to the wear of the running water and permitted the lake level to be rapidly lowered by the mere corrasion of the outflowing stream, but eventually a reef of limestone was reached by which the erosion was checked and the lake was held at a nearly constant level until its outflow was finally stopped by climatic changes which diminished the water supply. The level of the soft sill first crossed by the outflowing water is the level of the Bonneville shoreline at the nearest point where it is visible; the level of the limestone sill is coincident with that of the Provo shoreline; and the discovery of these facts correlated in a satisfactory manner the history of outflow with the history of the most conspicuous shorelines. As will presently appear, it was the work of the past summer to complement this knowledge by obtaining an interpretation of the Intermediate shorelines.

The detritus the waves bear away from one part of a coast is not all accumulated in the adjacent embankments; only the sand and gravel

are there collected, and the finer matter, which is capable of being held in suspension by the water for a longer time, is borne to a greater distance from the shore and finally settles to the bottom in the form of mud. Moreover, the streams which flow from the land to a lake bring with them each its quota of mud too fine to subside quickly, and this, too, is deposited in the depths remote from the shore. Thus the whole surface of every lake bottom becomes coated with a fine mud derived from the demolition of the surrounding land by rains and rivers and by waves.

Nor is this all: the wear of the rains and even the wear of the waves is not limited to abrasion, but includes also solution. All rock material is to some extent soluble by water, and every river carries to the sea or lake into which it empties not merely gravel and sand and silt, which are visible to the eye as impurities, but various minerals so intimately combined that the eye cannot detect them, although they are readily discovered by chemical tests. A lake which receives the water of a river or rivers, and is itself drained by an outflowing river, catches in its sediments the mechanical detritus only, which settles to the bottom where the current is checked, and permits all or the greater part of the chemical contents of the water to escape; but a lake with no outlet accumulates the entire mineral contents of the tributary streams, storing the mechanical detritus as a sediment, and the dissolved minerals either as a precipitate or else, by the aid of animal life, in some form of organic débris. The record of a lake is therefore written, not only by its wave-wrought shorelines, but by its mechanical and chemical sediments, and the investigation of Lake Bonneville necessarily included a study of the beds deposited upon its bottom. The work of the first year of the Geological Survey demonstrated the divisibility of these deposits into two members, separated by a break or interval during which no deposit took place. In the work of the second year the distribution of the two members and of the break were widely traced, so that now it is possible to give a comprehensive description of them.

In the central and deeper portions of the basin the section of the deposits is as follows:

First and lowest, the *Yellow Clay*, a fine, argillaceous, laminated deposit, with a pale olive tint where unoxidized, but exhibiting on weathered surfaces a dull yellow color. In a few spots this has been found interbanded with sand, but these interruptions are not continuous and its typical exposures exhibit clay only. Its thickness is unknown, the base of the deposit not having been seen, but 90 feet have been measured in one locality.

Second and highest, the *White Marl*, a fine, white earth, exhibiting little change from exterior to interior, and in its hardest varieties resembling chalk. Its thickness varies from 10 to 20 feet.

At all points the line of demarcation between the two deposits is strongly drawn, and at many points there has been found evidence

of a break in the continuity of the deposition at this horizon. This evidence consists in part of traces of erosion of the surface of the Clay before the deposition of the Marl, and in part of the local interpolation of various coarse deposits due to superficial streams.

These relations will be made clear by the diagram, which exhibits the lake strata in section at a point where they rest against a steep mountain slope of quartzite. The Clay and Marl (2 and 4) are fine in texture, and have their bedding marked by laminæ, which are nearly horizontal. In the direction to the left of the drawing they extend for many miles without interruption. The wedge of gravel which separates them, and the similar wedges above, are all restricted to the

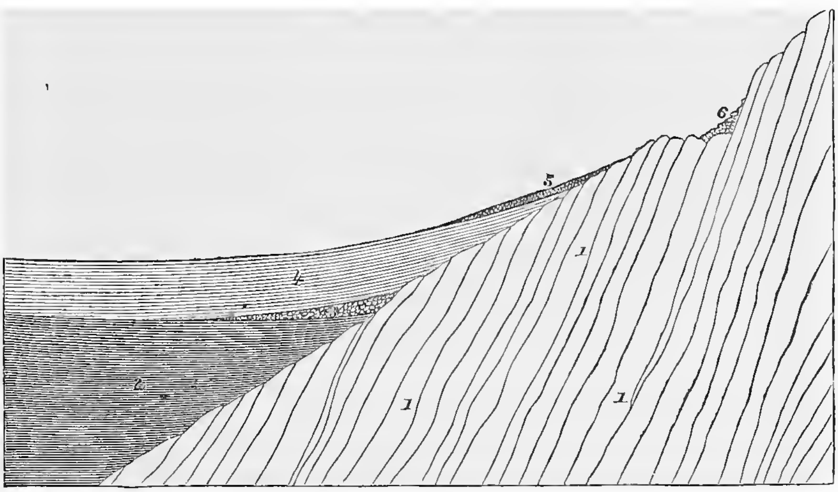


FIG. 17. Section showing the alternation of lacustrine and alluvial deposits at Lemington, Utah.
1. Paleozoic quartzite. 2. The Yellow Clay (lacustrine). 3. Wedge of alluvial gravel. 4. The White Marl (lacustrine). 5. Recent alluvial gravel. 6. Terrace and sea-cliff of the Bonneville shoreline, with recent talus at foot of cliff.

vicinity of the mountain; they are composed of fragments of the quartzite, cracked away by frost and washed down by rain. The process of their formation still continues, and those numbered 5 and 6 receive additions with every storm. When 2 and 4 were formed the lake bathed the foot of the mountain, and was the vehicle for the distribution of their fine material, but the intervening wedge of gravel, which was washed to its place by rain and rain-born rills, could not have been formed in the presence of the lake. It testifies, therefore, to a temporary subsidence of the water, and a drying of the bottom of the lake.

Neither the Clay nor the Marl passes beyond the limit marked by the Bonneville shoreline, but they rise upon the slopes on all sides until they merge with the shore deposits. As they approach the outer shorelines, however, they undergo changes of character and their distinctive features disappear. Their texture becomes coarser and they pass at many points into sands. In such case their separation can be made only where the evidence of the intervening break is present.

II. THE HISTORY OF THE OSCILLATIONS.

The general interpretation of these deposits and of their discontinuity is not difficult. The Yellow Clay was thrown down from deep and quiet waters, and therefore marks a period when the lake was large. It has been traced upwards along the slopes to within 200 feet of the highest water mark, and it is therefore known that the body of water to which it belonged attained at some time a depth of more than 800 feet, although there is no reason to suppose that that depth was continnously maintained through the whole period of deposition. The break between the two beds, with its local deposits of alluvium, records with equal clearness a period when the lake shrunk to small size, laying bare the surface of the Yellow Clay and exposing it to waste by running streams and to partial burial by subaerial agencies. This evidence has been traced continuously downward to a level only 200 feet higher than the surface of Great Salt Lake, and is there lost because modern erosion has exposed the section no farther. The shrunken lake could therefore have had no greater depth than 200 feet (plus the depth of Great Salt Lake), and its depth may have been much less. The White Marl, like the Yellow Clay, is a deposit from deep and quiet water, and unmistakably records a second rise of the lake. It has been traced as far up the slopes as the Clay, and there is some evidence, as will appear farther on, that it witnessed even a higher stage of the water during a portion of the period of its formation. Above the Marl the only deposits are shore embankments and recent alluvia, from which we are permitted to conclude that there has been no similar rise of the water since the retirement of the second flood.

There can be no question of this history so far as it goes, and any changes which may be made in it must be of the nature of additions. The climate of the region was moist and Lake Bonneville was large for a period represented by 90 feet and more of Yellow Clay; the climate was dry and the lake was small for an unknown period represented by the intervening alluvia; there was a second epoch of moist climate and expanded lake represented by 15 feet of White Marl; and that was followed by the present period of shrunken waters and dry climate.

But while this history is the necessary deduction from the facts in hand it does not include all of them, for it fails to account for the conspicuous difference in character between the Clay and the Marl. The character of the surrounding country affords no warrant for the belief that there was a large difference in the nature of the detritus brought to the lake during its two periods of maximum extent, and the explanation of the change in the character of the deposit must therefore be sought in the lake itself. The first hypothesis broached in regard to it was that

it was dependent upon the establishment of an outlet, but this had to be abandoned. The establishment of an outlet would undoubtedly produce a change in the character of the water and a corresponding change in the character of the sediment, but it could only occur during a period when the lake was exceptionally full, whereas the change indicated by the difference between the Yellow Clay and the White Marl occurred at a time when the lake basin was exceptionally empty. Moreover, the effect of an outlet upon the character of the water would be to deprive it of a large share of its dissolved matter, and therefore to give to its sediments a relatively pure mechanical character, whereas the sediment which actually formed in the deeper places after the change is especially characterized by carbonate of lime, a mineral almost necessarily brought to the lake in solution.

For the purpose of determining, so far as practicable, the ratio of the chemical to the mechanical elements in the sediments of the lake a series of specimens, selected to represent the Clay and the Marl, were subjected to chemical analysis. Each bed was found to consist of the same constituents, but in different proportions, as will appear by the following generalized table:

	Yellow Clay. Per ct.	White Marl. Per ct.
Carbonate of lime and magnesia (the lime predominant)	30	45
Silicates of alumina, iron, and other bases (alumina predominant)	35	20
Silica	35	35

The carbonates possess so high a degree of solubility that they may be referred to the rank of chemical deposits without hesitation. The silicates have so low a degree of solubility that they may be referred with equal confidence to the rank of mechanical sediments. The silica holds an intermediate position and may be either mechanical or chemical, or may belong in considerable share to each division. However the silica is assigned, there is no reason to doubt that it has the same origin in both deposits, so that in any event the Marl contains a relatively large proportion of matter derived by chemical precipitation and the Clay a relatively large proportion of material conveyed by the water in suspension.

With these facts in view a second hypothesis was broached to account for the lithologic difference. It is shown by the stratigraphy that in the interval between the deposition of the clays and the marls the water fell below the 200 feet contour, but the stratigraphy fails to show how far below that line it fell. There is no violence in the supposition that the water dried completely away so that no lake whatever remained, and that all of the salt that may have been contained in the original lake was deposited by desiccation upon the lowest part of the lake bottom. Nor is there any violence in the further supposition that during the dry period the silt brought down by rivers in time of freshet was spread over the bottom of the lake valley, mingling with the salt

at first and then covering it, until finally it was buried so deeply that the rising water, when the lake was again filled, did not redissolve it. By such a process the lake would be converted by desiccation from a salt body of water to a fresh body, and whatever influence loss of salinity might have upon the conditions of sedimentation would be indicated by an abrupt change in the character of the deposits.

For the verification of this hypothesis it is necessary to ascertain that the change which actually occurred in the nature of the sediment is such a change as would be produced by substituting fresh water for brine as the medium of sedimentation, and for its complete verification it would be necessary to probe the deposits in the lowest depression beneath Great Salt Lake and ascertain the existence of a heavy bed of rock salt. It was impracticable to undertake the latter investigation, but a series of experiments were conducted for me by Mr. Israel C. Russell, for the purpose of ascertaining what relation salinity of water bears to facility of sedimentation. No attempt was made to give a general character to the investigation, but it was made specifically applicable to the problem in hand by selecting for its materials the substances actually in question. The water of Great Salt Lake, which contains about 15 per cent of saline matter, was made to represent the supposed ancient brine of Lake Bonneville. The water of City Creek, a stream flowing through a calcareous district in the Wasatch Mountains and one of the tributaries of the Bonneville Basin, was taken to represent the water of Lake Bonneville in its supposed fresh condition, and specimens of the clay forming the lower bed of the lacustrine series were taken to represent the mechanical element of the Bonneville sediments. A chemist's beaker was filled with the brine, another with the creek water, and a series of others with various definite mixtures of brine and creek water. The clay was pulverized and divided into equal portions, which were severally added to the different beakers and mingled by stirring. Observation was then made of the time required by the different mixtures to become clear. The experiment was subsequently varied by preparing first those mixtures of which the clearing was found to be slowest, and then after an interval other mixtures observed to clear more rapidly, and then noting after what lapse of time they attained the same degree of approximation to clearness. It is unnecessary to give here the detailed results, but it is sufficient to say that they all point in the same direction and show that the clay falls much more rapidly from City Creek water than it does from the Salt Lake brine, while its rate of falling from various intermixtures is proportioned to the percentage of brine. The degree of clearness attained with the City Creek water in twenty-four hours was reached with the Salt Lake brine only after a lapse of five days.

Evidently, then, if Lake Bonneville possessed the salinity of Great Salt Lake its mechanical sediment would be much longer retained by the water and would therefore be more evenly distributed than if it was charac-

terized by the freshness of City Creek; and since the mechanical sediment necessarily entered the lake at its margin, being derived from the tribute of muddy streams and from the waste of the coast under the action of waves, it would in a fresh lake be largely deposited in the neighborhood of the shore, while in a salt lake it would be transported to greater distances before reaching a final resting place, and although possibly the upper slopes would still receive the lion's share a considerable portion would nevertheless find its way to the central region. The hypothesis of a loss of salinity during the interval between the deposition of the Yellow Clay and the White Marl accords therefore with the observed difference between those deposits. The upper and later-formed deposit, which hypothetically marks the prevalence of fresh water, is characterized by a smaller proportion of mechanical sediment, and its calcareous constituents, which thus acquire relative importance, are rendered conspicuous.

It is a necessary part of the hypothesis that the contrast of sediment exhibited by the Marl and Clay in the central area is reversed at the margins of the basin; for if it is true that the material furnished to the lake had always the same character, and that the contrast of the upper and lower deposits of the central area depends on conditions of distribution, then the small clay content of the White Marl at the center should be complemented by a large clay content of the shoreward prolongations of the same deposit; and in peripheral regions the lower bed should be more calcareous than the upper. As a matter of observation this has not been shown, but at the same time it has not been disproved. Both Marl and Clay become so variable and so coarse in the vicinity of the shores that a concise diagnosis of their constituents is impracticable. Whatever calcareous matter they contain is so masked by silicious and argillaceous material that it does not affect them in a manner appreciable to the eye, and chemical determination could not be brought to bear by reason of their variability, which made it impossible to select representative specimens.

It is possible that the contrasted conditions afforded by brine and fresh water may conduce to the observed disparity of sediments in yet another way. It is a familiar fact of the laboratory that the mingling of concentrated solutions of common salt and of carbonate of lime induces a precipitation of carbonate of lime, and although such a result is not observed when the waters of City Creek and Great Salt Lake are mingled, it may nevertheless be possible that a reaction of that nature took place about the margins of Lake Bonneville in its supposed briny phase. If it occurred, then the chief part of the chemical sediment would be accumulated near the shores, while a relatively small share would reach the central region. Afterward, when the water was freshened, the precipitate would in the absence of this reaction be equable in all parts, and a relatively greater proportion of carbonate of lime would be thrown down in the central region. It is noteworthy, however, that the off-

shore equivalents of the Yellow Clay afford to superficial observation no indication of the presence of an exceptional share of precipitated carbonate of lime; so that while this consideration might help to sustain the general hypothesis it is not definitely sustained by facts of observation.

On the whole, the theory that the lake became fresh by desiccation finds too little positive support to entitle it to unreserved acceptance, but is controverted by no single known fact, and may therefore be considered to hold the position of a plausible working hypothesis. A series of investigations which have already been initiated by Mr. Russell in regard to the deposits of numerous natural evaporation pans of the Great Basin must eventually enable us to form a better judgment in regard to it than is possible at present. If it shall be established, a valuable addition will be made to the history of the ancient lake, for it will be shown that the climate in the inter-Bonneville epoch was so much drier than the climate of the present day that the water surface of the basin, which now has an extent equal to one tenth that of the broadest area of Lake Bonneville, completely disappeared. In our tentative history of the lake and the climate, subject always to revision with the addition of new facts, we cannot do better than to incorporate this element.

We now turn from the history written by the sediments to the contemporaneous history written by the shorelines.

Before the existence of Lake Bonneville its basin was dry, or nearly so. The water rose at the beginning of the epoch represented by the Yellow Clay, and receded to the base of the slope at the close of that epoch. It rose and fell again at the beginning and end of the epoch represented by the White Marl. Thus its margin was carried four times over the slopes of the basin, and every part of the profile was four times subjected to the action of the waves. In localities so circumstanced that the work of the waves was destructive, a portion of the land being eaten away, each successive attack cut deeper into the rock or earth and obliterated the traces of preceding attacks. In localities so circumstanced that the work performed by the waves was constructive, embankments of detritus being added to the pre-existent surface, each successive advance or recession built its embankments upon those which had previously been made and wholly or partially concealed them. The series of shorelines last formed are, therefore, generally speaking, the only ones visible, and the actual configuration of the surface is, in general, that wrought by the last passage across it of the water margin. Since the water is now at low stage, the last passage was a recession, and it was therefore assumed, both by the writer and by others, during the earlier progress of the study of the lake, that all of the visible shorelines represent lingerings of the water during its last recession. When, however, it became known that the portion of that recession included between the Bonneville and Provo shorelines was caused by the gradual

cutting away of the barrier at the point of outlet, a difficulty arose, for the interval between the Bonneville and Provo shows in many places a number of well-characterized (Intermediate) shorelines, and it appeared strange that the rate of lowering should have been so irregular as to have permitted their formation. It was at first suspected that the lingerings of the water might have been determined by ledges of exceptional hardness in the material through which the outflowing channel had to wear its way, but an examination of the point of outlet gave no indication of the existence of such ledges. The idea then suggested itself that the phenomena were due to oscillations of climate, whereby the volume of discharge had been alternately increased and diminished, so that the rate of erosion had been alternately rapid and very slow; and with a view to testing this theory an elaborate study of the groups of embankments associated with the Intermediate shorelines was undertaken. The result of the investigation was entirely unexpected, but was none the less satisfactory, for it included a determination of the order of succession of nearly the entire series of shore marks.

When two embankments formed at successive water stages are so far separated upon a pre-existent slope that they are entirely distinct, they afford no means of determining their relative age, but if they are contiguous, one must always overlap the other in some way, and the determination of this overlapping serves to establish the order of priority. Thus, if the line *a b* of the diagram is the profile of a pre-existent slope upon which the series of shore embankments 1, 2, 3, and 4 have been built, then it is impracticable to determine the relative age of 2 and 3 or of 2 and 4, but it is evident that 1, which rests upon 2, must have been later formed, and that 3 was built before 4 which rests against it. This relation is not expressed by the external forms, for the profile of the group 1–2, is identical with that of the group 3–4, but purely by the manner in which they are superposed. To make the de-

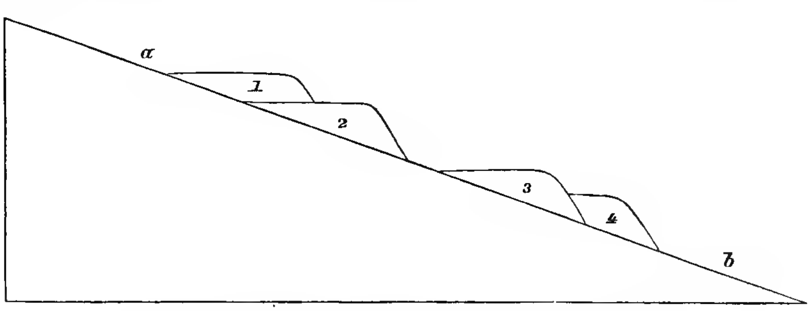


FIG. 18.—Diagram illustrating the superposition of shore embankments.

termination it is necessary to have a cross-section, and in the embankments of the Bonneville Basin cross-sections are rarely exposed, for the reason that the recency of their formation has given subsequent erosive action little opportunity to perform its work. Nevertheless,

a few localities were by patient search discovered, and although none of them sufficed to tell the entire story it was found possible so to combine their elements as to develop a tolerably complete history of the series of events by which the Intermediate shorelines were produced.

A graphic transcript of that history is given in Figure 19, where the chronologic order of the deposits is, first Y, then I, J, K, L, M, B, and P. The series of embankments YY was not discovered in section and the succession of its parts is unknown. I, J, K, L, and M, are the embankments of the Intermediate shorelines and their order of formation was from below upward; that is to say, they were built by the rising water and not by the falling. B is the Bonneville shoreline, formed after the completion of the Intermediate; and P, the Provo, last of all. The series YY records the first rise of the water and is the littoral equivalent of the Yellow Clay. It shows that the water at that time reached an extreme level about ninety feet lower than the Bonneville shore, and by so much failed to attain the height necessary to produce an overflow. The overlying banks from B to P record the second rise of the water and are the littoral equivalents of the White Marl. Their order of succession shows that the water rose by gradual stages until it reached its maximum at the Bonneville shore, and then, when an overflow had once been established, cut away the barrier and fell to the

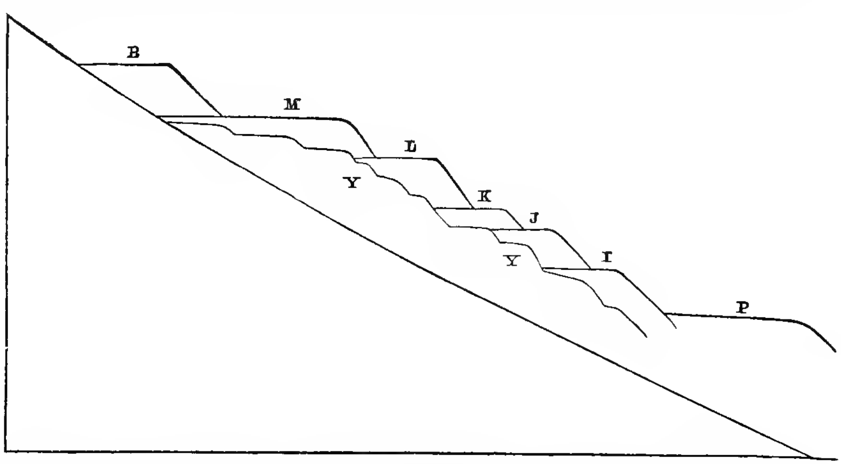


FIG. 19.—Diagram, showing the Overlap and Chronologic Order of the Shore Embankments of the Bonneville Basin.

Provo level with a rapidity that afforded no opportunity for a record of the stages of its progress. At the Provo level the water was long retained by the resistance of the limestone sill at the point of outlet, and embankments of exceptional magnitude were formed on its shores.

It is especially interesting to learn that the second rise was higher than the first, for this fact carries with it the conclusion that the second great wave of climate was more strongly characterized by moisture than

the first. Combining this information with that afforded by the sediments, we have the two climatic maxima distinctively marked: the first was long and relatively mild; the second was short and relatively intense.

It remains to consider the beginning of the Bonneville history. The history of the lake is written by wave-sculptured topography and by lacustrine deposits. The history of the basin before the lake is written by rain-sculptured topography and alluvial deposits.

We are unaccustomed to think of the ordinary forms of land as a work of sculpture, but that is none the less their origin. If we except those restricted areas which have received their configuration from the recent occupation of lakes and oceans and those other restricted areas which owe their shapes to the passage of glaciers and the heaping of glacial débris, the whole surface of the land exemplifies the plastic art of the rain. The work of the wind is accessory to it; subterranean forces of upheaval and of volcanic energy give rise to mountain masses, and variations of hardness in the rocky strata of the earth assist in determining the positions of hills and crests and ridges; but rain is the agent which actually develops the forms we see. It penetrates rocks and dissolves them; swollen by frost it disintegrates them; it beats upon them and washes away the fragments, and gathering in rills, creeks and rivers it erodes channels and carries the débris to the valleys and the ocean. Its work is in the highest degree systematic, persistent and complete, and it either has molded or is molding every geographic form of nature to exemplify the laws of its action. Our eyes are so accustomed to these forms that we unconsciously anticipate them and readily detect the exceptional nature of all differing elements of sculpture. The sculpture wrought by the waves affords so marked a contrast that the eye distinguishes it at once, and it is thus that the tracing of the Quaternary lakes is made possible.

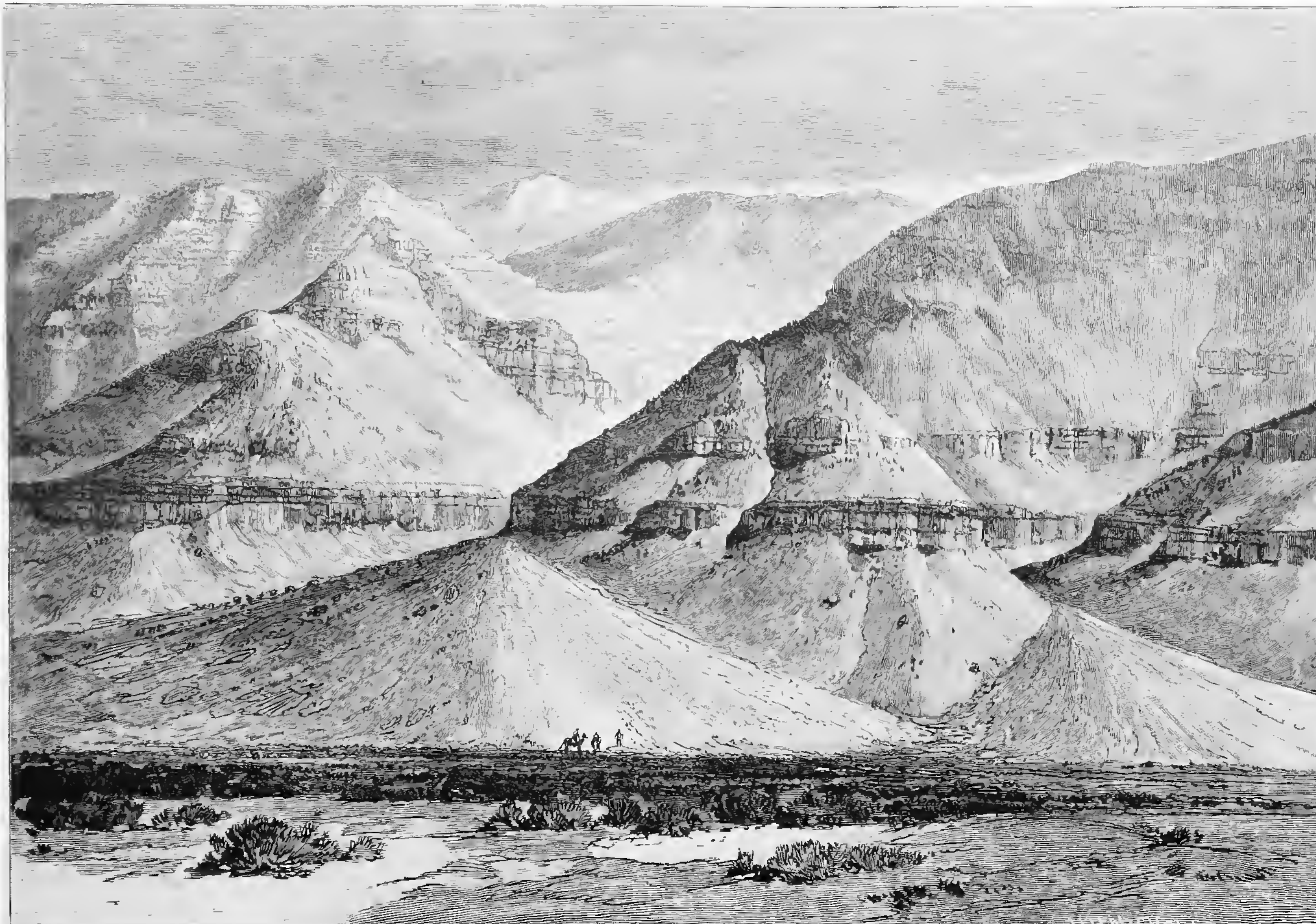
The sculpture of a mountain by rain is a twofold process; on the one hand destructive, on the other constructive. The upper parts are eaten away in gorges and amphitheaters until the intervening remnants are reduced to sharp-edged spurs and crests, and all the detritus thus produced is swept outward and downward by the flowing waters and deposited beyond the mouths of the mountain gorges. A large share of it remains at the foot of the mountain mass, being built into a smooth sloping pediment. If the outward flow of the water were equal in all directions this pediment would be uniform upon all sides, but there is a principle of concentration involved whereby rill joins with rill, creek with creek and gorge with gorge, so that when the water leaves the margin of the rocky mass it is always united into a comparatively small number of streams, and it is by these that the entire volume of detritus is discharged. About the mouth of each gorge a symmetric heap of alluvium is produced—a conical mass of low slope, descending equally in all directions from the point of issue; and the base of each mountain ex-

hibits a series of such alluvial cones, each with its apex at the mouth of a gorge and with its broad base resting upon the adjacent plain or valley. Rarely these cones stand so far apart as to be completely individual and distinct, but usually the parent gorges are so thickly set along the mountain front that the cones are more or less united and give to the contours of the mountain base a scalloped outline.

The Bonneville Basin is surrounded by and interspersed with mountains, and from the summits of these down to the Bonneville shore the entire topography is of a rain-wrought type. From the shoreline downward to the valleys and plains its nature is composite, uniting the elements of wave sculpture with those of rain sculpture, but the manner of union is not indiscriminate and in it is written what we know of the pre-Bonneville history of the basin. All of the larger elements belong to the domain of rain, and upon these the elements derived from wave-work are lightly engraved and embossed. The alluvial cones of the mountains do not find their bases at the level of the upper shoreline, but extend downward uninterruptedly to the bottoms of the valleys, while the shorelines are wrapped about them, all of the greater capes and bays being determined by a pre-existent, rain-wrought configuration. Rain therefore dominated the basin before the lake, and the basin was empty for a long period before it was full.

The same story is told by the deposits. The alluvial cones are subaerial deposits, the lake beds subaqueous; and wherever a section of the latter is obtained upon the margins of the basin they are found to overlie unsorted accumulations of alluvium. The two are so distinct in character that they cannot be confused. The lake beds are fine earths, evenly laminated, and of great uniformity throughout the central district. Toward the margins they usually become coarser, passing into sands at first and being finally exchanged at the shore for thoroughly sorted gravel, smoothed and rounded by the rolling action of the waves. In the alluvial deposits no stratum is widely continuous and few are homogeneous, but coarse and fine fragments are mingled indiscriminately or with an obscure and lenticular bedding.

Form and substance thus conspire to prove that the lake had a beginning as well as an end, and that before its inception the basin was for a long time subjected to the ordinary laws of sculpture by the action of rain. It must not be supposed, however, that the period of exclusive rain sculpture was one of great aqueous precipitation, but rather the contrary. A large rainfall would fill the basin and subject its lower parts to lacustrine influence. Only a small precipitation, or a climate of relative aridity, could leave the lower valleys dry and give the entire slope to the unrestricted action of such rain as fell. The evidence of ancient rain sculpture in the lower slopes is therefore in this case the evidence of an arid climate instead of a humid one, and our data warrant the belief that the Bonneville epoch was an episode of moisture interpolated between the aridity of the present day and the aridity of the past.



ALLUVIAL CONES.

It is probable that with the diminished rainfall of the present day the wear of the mountains is slower than during the Bonneville epoch, and it is probable that it was similarly slow during the ante-Bonneville period of aridity. Detritus was therefore furnished less rapidly for the construction of the old alluvial cones than for the building of lake strata, and the magnitude of the cones as compared with the lake beds would lead us to ascribe an immensely greater duration to the ancient dry climate than to the epoch of moisture. It is to be borne in mind, however, that a moist period could make its record by shorelines and lake beds only on the condition of the existence of a closed basin, and it is a matter of geologic history that the Bonneville Basin came into being after the deposition of the latest Tertiary deposits known in the region. It is impossible to tell what fraction of the work of the construction of the alluvial cones was performed after the occurrence of the upheavals and subsidences to which the basin owes its origin, and it is therefore impossible to assign even a proximate limit to the duration of the dry epoch demonstrated to have preceded the Bonneville humidity; but it may be asserted with confidence, that the duration of the earlier period was not merely greater than that of the Bonneville but many times greater, for the condition of the various passes which constitute the lower parts of the rim of the basin suffices to show that the waters were not discharged for a very long period antecedent to the Bonneville outflow.

It follows from what we have said of the sculpture of mountains that an alluvial foot-slope is a necessary concomitant of an angular summit. It is impossible that the higher parts should be carved into peaks and scored into gorges without the accumulation of eroded material at the foot of the slope. But in the central parts of the Bonneville Basin, in the midst of the Great Salt Lake Desert, there are mountain peaks springing abruptly from the lake sediment without visible pediments of alluvium. They jut from the plain as abruptly as islands jut from the ocean, and the resemblance is so striking that it has caught the eye of the frontiersman and prospector, and the peaks have received such names as "Silver Islet," "Desert Island," and "Newfoundland." The resemblance involves something more than mere analogy, for they are really submerged, having their bases buried by the lacustrine deposits of Bonneville and earlier lakes. They serve to carry us back one step farther in the history of the basin, for they record a time when the visible lacustrine strata did not exist and when the relation of altitudes was such that the detritus from the peaks, instead of being arrested where it now is by the plain, was free to descend the slope for an additional distance of at least some hundreds of feet. At that time the basin may not have been a basin and may have permitted its drainage to escape to the ocean; but during the whole period required for the burial of the mountain bases its barriers must have been in existence so as to render the desert the repository of detritus. Before Bonneville Lake,

therefore, there was a long history of smaller lakes in the Bonneville Basin. This history we cannot read in detail because the sediments which record it lie beneath the plain, completely buried by those of the later lake.

Putting together all these several elements we may construct the Bonneville history with some confidence:

1. A long period of dry climate and low water, during which the mountains of the desert were buried and the alluvial slopes of marginal mountains were formed.
2. A period of moist climate and high water, during which the Yellow Clay was deposited and the shore was carried within ninety feet of the summit of the lowest barrier of the basin.
3. A period of extreme dryness, during which the lake disappeared and its salt was buried.
4. A relatively short moist period, during which the White Marl was thrown down and within which the water overran the barrier, diminishing by erosion its height at the point of discharge.
5. The present period of relative dryness.

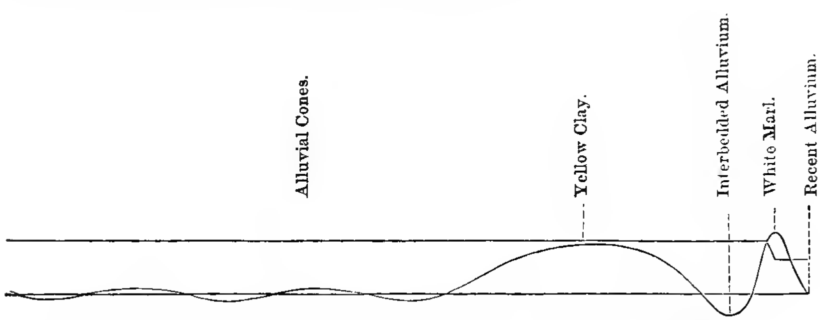


FIG. 20.—Curve of the Quaternary Oscillations of Climate, as recorded by Lake Bonneville.

In the diagram an attempt has been made to give a graphic representation of these oscillations of climate. The lower horizontal line represents the dry climate of the present day. The upper horizontal line represents a climate with such a degree of moisture as to permit the basin to overrun its rim. The relative proportions of the curve are, of course, tentative and crude, for the investigations have afforded no absolute time gauge and very little that can be interpreted in time ratios. We know that the moisture was greater at the time of the second rise than at the time of the first, but have no means of telling how much greater. We know that the earlier rise was of longer duration than the later, but do not know how much longer, because the Yellow Clay which represents it has never been seen in complete section. It is theoretically probable that the inter-Bonneville dry epoch was characterized by a climate more arid than the one we experience, but we cannot say how much its aridity exceeded the present, and of its duration we only know

VIEW ON GREAT SALT LAKE DESERT, SHOWING MOUNTAINS HALF BURIED BY LAKE SEDIMENTS.

that it was far briefer than that of the dry period preceding the first rise of the water.

If it were possible to replace this tentative curve by the actual curve of climatic oscillation for the same period, we should undoubtedly have a form less simple in its character. Indeed, there is abundant evidence that each great rise and fall recorded by the shorelines of Lake Bonneville was interrupted by intervals of reverse motion, the rising water occasionally hesitating and sinking for a time, and the falling water occasionally oscillating upward. It may be asserted with some confidence, however, that the history includes but two *great* waves. If the water had many times, instead of twice only, risen to the upper levels of its range, the tell-tale sediments could not have failed to record the intervening subsidences.

The student of the climate of the Glacial Epoch will be interested to compare this history with that deduced from the glacial beds of Europe and the United States, and if he correlates the second humid wave with the Reindeer Epoch of English geologists he will be surprised to find that in Utah the climate was more severe than during the first maximum, although maintained for a shorter period. It is yet too early, however, for final conclusions, for the Bonneville history is but one of a group, and when Lake Lahontan and the other lakes of the ancient family have received a similar treatment the conjoint verdict of the whole may be notably different from the single verdict of an individual lake. There is a partial blank in this history, regarded as a history of climate, embracing the period while the lake overflowed, for then its water level ceased for a time to be an index to the amount of precipitation. There is another partial blank during the inter-Bonneville desiccation. It is by no means improbable that these will be filled by the evidence to be gleaned in other valleys of the Great Basin.

Before leaving the subject of the chronology of the lake, I cannot forbear to add my testimony to that which other geologists have rendered of the extreme brevity of the Quaternary as compared with other divisions of geologic time. If it could be measured in years its extent might excite our wonder, but when gauged by those imperfect standards to which geologists are limited it appears of extreme insignificance because overshadowed by the greater magnitude of all other elements of geologic duration. The weight of the bowlder which we strive to lift may seem great because our strength is small, but it is a mere trifle as contrasted with the distant hill, and we have no terms by which to compare it with the mountain beyond. Such differences the geologist must confess his inability to measure, but he is none the less impressed with their magnitude.

If we attempt to compare the duration of the Bonneville epoch with that of earlier portions of geologic time, we find no criteria available except those afforded by the relative thickness of the accumulated

deposits, and these are practically valueless because rates of deposition are entirely controlled by extraneous conditions of which we have no knowledge in the case of the older deposits. A better, but yet a very inadequate, idea may occasionally be gleaned of the relative antiquity of different events by comparing the subsequent erosion. Rain, the great sculptor of natural forms, attacks all exposed surfaces of land, and whatever may have been their original shapes, works them over until they accord to certain types embodying a certain system of laws. Its attacks are renewed with unwearied persistency until its ends are accomplished. The sediments of a dead lake are measurably protected from it because they occupy depressions and have few slopes steep enough to be worn by running water, but shorelines are fully exposed and are powerless to resist. Nevertheless, the Bonneville shores are almost unmodified. Intersecting streams it is true have scored them and interrupted their continuity for brief spaces, but the beating of the rain has hardly left a trace. The sea cliffs still stand as they first stood, except that frost has wrought upon their faces so as to crumble away a portion and make a low talus at the base. The embankments and beaches and bars are almost as perfect as though the lake had left them yesterday, and many of them rival in the symmetry and perfection of their contours the most elaborate work of the engineer. There are places where bowlders of quartzite or other enduring rock still retain the smooth, glistening surfaces which the waves scoured upon them by dashing against them the sands of the beach.

When this preservation is compared with that of the lowest Tertiary rocks of the region—the Pliocene beds to which King has given the name "Humboldt"—the difference is most impressive. The Pliocene shorelines have disappeared. The deposits are so indurated as to serve for building-stone. They have been upturned in many places by the uplifting of mountains; elsewhere they have been divided by faults, and fragments dissevered from their continuations in the valley have been carried high up on mountain flanks, where erosion has carved them in typical mountain forms.

If we look back to the lower Tertiary of the adjacent plateau region of Utah, Colorado, and Arizona, we find a still greater contrast, for the Eocene of the Colorado Basin has not merely lost its shorelines and been upturned and faulted; its whole great sheet, with the exception of a few marginal fragments, has been excavated and carried away, and with it have disappeared several thousands of feet of the strata that lay beneath it.

The date of the Bonneville flood is the geologic yesterday, and calling it yesterday we may without exaggeration refer the Pliocene of Utah to the last decade; the Eocene of the Colorado Basin to the last century—and relegate the laying of the Potsdam sandstone to prehistoric time.

III. THE LAKE AND THE GLACIERS.

All geologists who have studied the Quaternary lakes of the Great Basin and at least one student of a Quaternary lake of the Old World, have agreed in regarding them as the contemporaries of the Quaternary ice-fields, but their conclusions have been reached purely by analogy. The moraines and other traces left by the ancient ice-fields are so fresh in their appearance, so little impaired by the waste of time, that they are regarded as the record of an epoch immediately preceding the present time. The same is true of the shorelines and deposits of the ancient lakes. It is further known that the Epoch of Ice was preceded by a still longer epoch not so characterized, just as the Bonneville Epoch was preceded by a longer epoch of relative dryness. More than this, the changes of climate were analogous in character. It is a matter of dispute whether the Glacial climate differed from that which preceded and followed it by an excess of moisture, or by a lowering of temperature, or by both. But whatever was its character it must have been one in which the ratio of precipitation to evaporation was relatively great; and that is the sole condition necessary to the production of the Quaternary lakes. But while this analogy is cogent and the conclusion to which it leads finds no opponent, it would, nevertheless, be more satisfactory to establish the relation by direct observation, and it was therefore with great interest that attention was turned during the field work to a locality at the western base of the Wasatch Range where the moraines of three ancient glaciers stretch below the limit of the ancient lake. It was anticipated that if the glaciers attained their maximum development after the culmination of the lake their moraines would be found either to consist partly of plowed-up lake beds or else to rest upon lake beds; and if the history of the lake was subsequent to that of the glaciers, it was anticipated that the moraines would be found partially buried by the lake sediments or else scored by the shorelines. Neither of these anticipations was realized. Two of the terminal moraines were found to be entirely dissociated from the lake beds, so far as could be ascertained, and they bear no trace of wave sculpture. The remaining terminal, that of Little Cottonwood Cañon, is partially buried by a sandy deposit that bears some resemblance to a river delta, but which has been so deformed by a system of faults by which the region has recently been shattered that its true character cannot be asserted with confidence. The locality failed therefore to yield the crucial evidence for which search was made, and practically afforded no contribution to the subject. There is reason to hope, however, that a series of localities announced by Mr. Russell as recently discovered upon the eastern flank of the Sierra Nevada will prove more communicative. His reconnaissance has served to show that the glaciers there descended and retreated more than once, and that their history has a determinable relation to that of the Quaternary predecessor of Mono Lake.

IV. THE LAKE AND VOLCANIC ERUPTION.

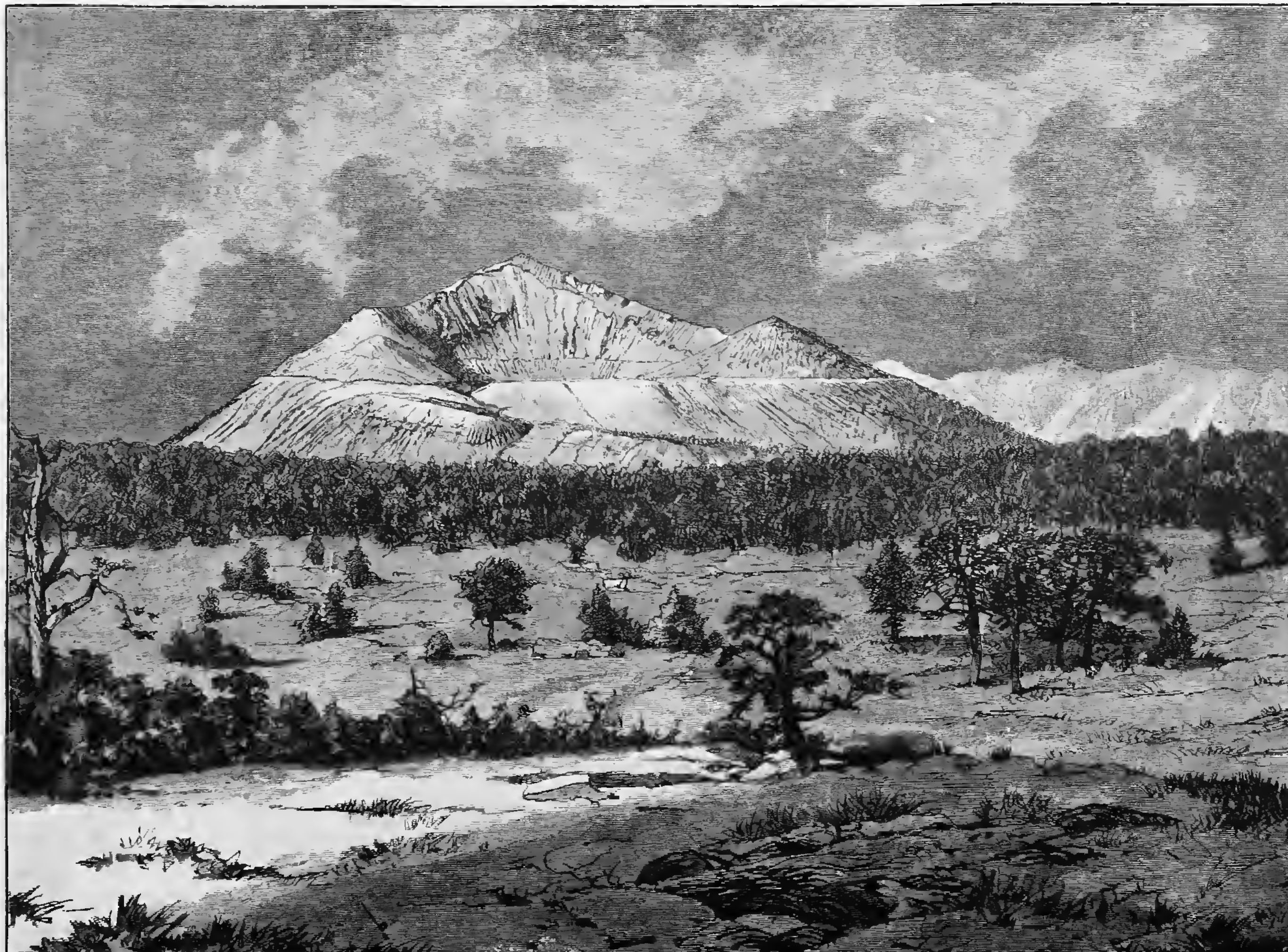
The discovery of Richthofen that the various lavas erupted in Western North America had a definite, uniform order of sequence has been abundantly verified by all later investigations. And not only do his successors in that field of inquiry find the order of sequence in every place the same, but some of them at least are disposed to assign a definite geologic date to the appearance of each variety of eruptive rock. The cycle of eruptions to which his conclusion applies belongs to the Tertiary and Quaternary history of the region, and the latest in order of the erupted rocks is basalt. Basalt is therefore the only volcanic rock the western geologist would expect to find associated with the phenomena of the Quaternary lakes, and so far as Lake Bonneville is concerned it certainly is the only rock thus associated. The only other eruptive rock known to appear within the circle of the shorelines is rhyolite, and all of its masses are so ancient that they have lost by erosion all traces of their original forms. The same may be said of some basaltic masses, but the greater number still preserve their original tabular shapes, and a few are still furnished with craters of cinder and slag. The majority evidently antedate the epoch of the lake, for they bear upon their sides the sculptured shore marks, and support on their flanks or backs the lake-spread sediments. To this rule, however, there are a few exceptions, and these serve to bring down the period of basaltic eruption to a date subsequent to the last rising of the water.

In the vicinity of the town of Fillmore the Sevier Desert is diversified by a group of hills composed of volcanic ejecta, recording the latest plutonic activity within the Bonneville Basin. The extravasated material appears in three forms, viz., *coulées* of lava, cratered cones of slag and cinder, and cratered cones of tuff.

The *coulées* are of the usual type, but by reason of the flatness of the surface upon which they flowed they are broadly spread, so as to constitute fields rather than streams of lava. In the interior they are of compact basalt, but superficially they are for the most part greatly inflated by bubbles.

The cratered cones mark in every case the points of issue of *coulées* and are themselves the product of explosive action. They are composed entirely of fragments which were hurled into the air from the vent and fell about the sides, piling up circular barriers, and they are of two distinct kinds, characterized by two kinds of fragments, slag and tuff.

In the case of the slag cones there is every evidence that a large share of the ejected material was either molten or pasty at the time it reached the earth, the successive pellets being flattened out by the force of the impact and fitted to the surfaces upon which they alighted. The in-



PAVANT BUTTE, A SUBMARINE VOLCANO.

teriors of the craters are stuccoed with clots of spongy lava, which adhered in so soft a condition as to flow and drip more or less after they became attached. Besides these pasty masses there is a great quantity of light, brittle, spongy material, such as has been called "cinders" and "lapilli," and it is possible that this constitutes the greater bulk, but the surfaces are largely composed of taffy-like slag.

In the tuff masses, on the other hand, there is nothing to show that any of the ejected material was soft at the time it reached its resting place. Lapilli or cinders, similar to those which enter into the composition of the slag cones, but finer grained, make up nearly the entire mass, and are cemented together in a coherent body which betrays an obscure bedding and has everywhere a brecciated appearance; in it are embedded at rare intervals both rounded and angular fragments of basalt, and these, although they have evidently reached their position by violent ejection, are not of a scoriaceous or frothy texture, but are compact. These cones appear to have been formed by subaqueous eruption, and are free from slag because the presence of water made it impossible for small fragments to escape from the vent in a hot condition.

The most conspicuous of the cones is Pavant Butte, otherwise known as the Sugar Loaf, which stands solitary on the plain, midway between the towns of Fillmore and Deseret. It is composed exclusively of tuff and does not form a complete ring, but has a semi-lunar base, and appears never to have been closed upon the south side. Midway between its base and its summit it is encircled by a terrace, carved by the waves at the highest stage of the lake, and there is evidence that the two processes of wave sculpture and volcanic construction were carried forward, in part, simultaneously, a first incision by the waves having been filled by new ejecta, and then partially reopened by later wave action. Pavant Butte, therefore, is the product of eruptions which occurred while the desert was covered by the lake, and the last addition to it was made during the highest stage of the lake.

At its base, and apparently constituting its foundation, there is a lava-bed half concealed by lacustrine sediments, but these sediments consist only of the White Marls, and nowhere exhibit the underlying Yellow Clay. It is probable, therefore, that the *coulée* outflowed during the inter-Bonneville epoch of low water.

A second crater, to which the name Tabernacle has been attached, is surrounded by two rims, the outer and older of which consists of tuff and the inner and newer of slag. No shorelines are carved on either tuff or slag, and no lake beds rest upon them. The eruption began, therefore, during a high stage of the lake and was continued or renewed after the water had fallen below the level of the vent. There is reason to believe, however, that the lake had not entirely disappeared, for a lava field which outflowed from the same vent during the formation of the slag cone, bears upon its outer margin the traces of the Provo shoreline. There is evidence also, in the exceptional thickening of the

lava bed at its outer edge, that it encountered as it flowed the refrigerating influence of standing water, and it is therefore concluded that the date of the last eruption from this vent was during the Provo stage of the lake or just before the final subsidence of the water.

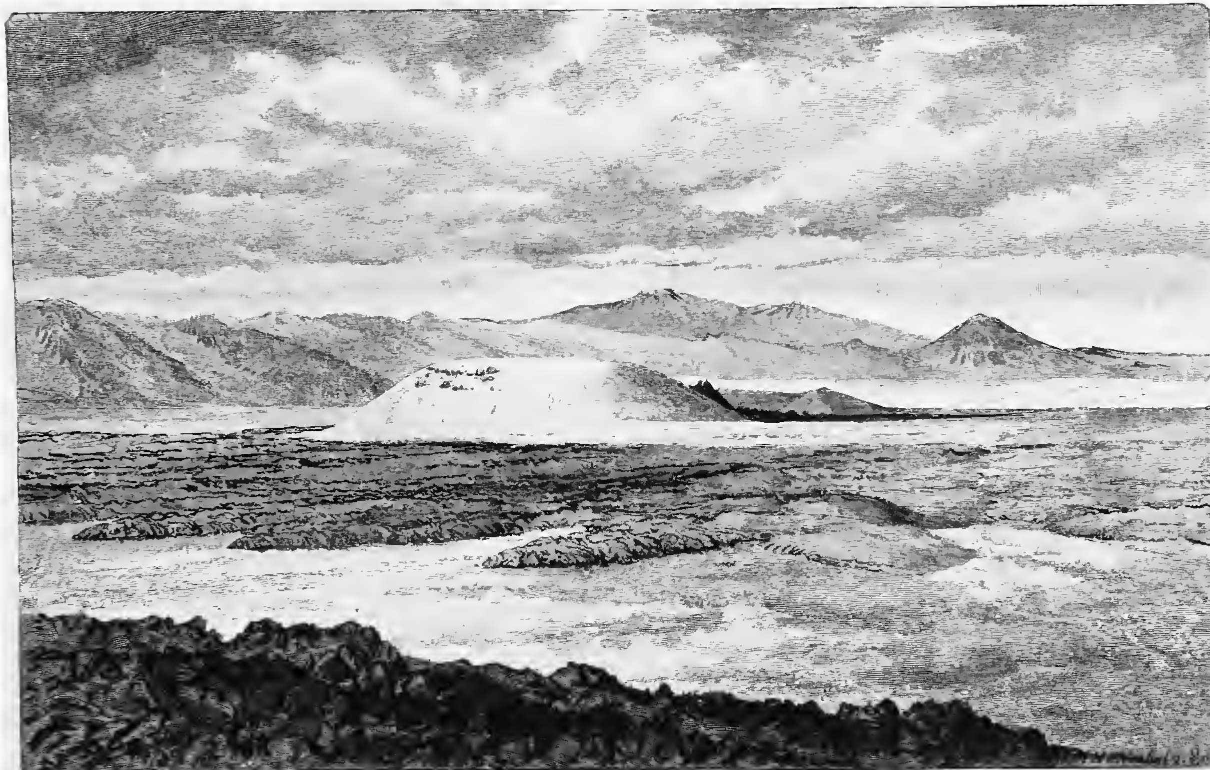
A third group of craters, known as the Ice Spring group, is still more recent, and with its associated *coulées* overlies the latest of the lake beds, while no shorelines whatever impinge upon it.

The period of volcanic activity therefore continued entirely through the epoch of the lake, and was brought down so nearly to the present time that there is no warrant for assuming that its end has yet been reached. No one who has seen the fresh, black, unworn surfaces of the most recent *coulées*, still absolutely barren of vegetation, could be affected by surprise if it should some day be announced that the now quiescent fires had again broken forth.

V. THE LAKE AND MOUNTAIN BUILDING.

It is not many centuries since the learned and ignorant alike regarded mountains as the embodiment of stability and permanence; but since the birth of geology it has been abundantly shown, first, that the sites of many individual mountains were in the remote past occupied by plains or oceans; second, that in the remote past there were mountains where now are only plains; and, third, that on account of the unceasing erosive work of the elements no mountain can be permanent. Each mountain therefore has a history,—involving its inception, its growth, its decay, and finally its extinction. With slight exception all mountain growth is by subterranean action, and if we exclude volcanic mountains from consideration we may refer mountain building almost wholly to upheaval. With slight exception the destruction of mountains is by erosion, and in most mountains the formative and destructive processes at some time coexist. So soon as the formation of a mountain is initiated, slopes are created which enable rain and streams to wear away its surface, and since this wear never ceases until its final and complete destruction, it is contemporary with every stage of growth except the initiative. The magnitude of each mountain at any time represents the excess of formation over destruction, of upheaval over erosion. Actual increase takes place only when the growth exceeds the decay, and actual decrease only when the decay by erosion is more rapid than the growth by upheaval.

Up to this point all geologists are agreed; but there is a difference of opinion in regard to the rate of formative action, and upon this difference investigators may be regarded as divided into two classes, each of which represents a tendency of thought. On the one hand are those who conceive that each mountain rose more or less abruptly, either by a sin-



TABERNACLE CRATER AND LAVA BEDS.

gle movement at a definite point of time, or else by a small number of such movements separated by long intervals of time. On the other hand are those who think the formative movement is continuous and slow, variable indeed in its rate, but never in any large way paroxysmal. Undoubtedly there are still others who hold to a middle ground of opinion, but in a general way geologists tend to catastrophism on the one hand or to uniformitarianism on the other.

Neither of these views is open to the charge of being purely speculative, but each can claim in its support a body of unquestioned facts of observation. The advocates of each include men of wide experience in the direct study of nature, and who must be supposed to have founded their ideas upon that study, and not to have been controlled by such preconceptions as closet philosophy is apt to engender.

The two theories in regard to the origin of mountains are correlated, however, with certain notions concerning the condition of the interior of the earth, which are necessarily to a great extent speculative. To the catastrophist it is natural to conceive the crust of the earth as a body of great rigidity and strength, resisting the force applied to it by subterranean action until by cumulation it had become very great, and then suddenly yielding. To the uniformitarian it is natural to conceive the crust of the earth as in a high degree mobile, responding promptly to all subterranean influences and reflecting them in the configuration of its surface. These differences of view are in the main independent of those other differences which are concerned with the thickness of the crust, and some physicists who are disposed to assign a great thickness to it or even to regard the entire mass of the earth as solid are at the same time of the number who ascribe an extreme mobility to its material.

To the catastrophist the growth of each existing mountain is a work of the past, the present day witnessing only its decay. He does not necessarily regard the work of mountain making as complete and look to the gradual extinction of mountain masses from the present time onward, but he at least views the present as a period of inactivity and conceives the mountains of the future as the products of paroxysms yet to occur. To the uniformitarian the present is, equally with the past, an epoch of mountain building, and whether the present rate be more rapid or less rapid than that of the past, the process is ever the same. He therefore expects to obtain from a study of that which is actually transpiring such criteria of judgment as will enable him to understand the revolutions of the past.

Erosion begins with the inception of a mountain, but is at first a slow process, because the gentle initiative slope gives to flowing water only a small velocity, and with a small velocity its erosive power is feeble. As the mountain rises the declivities of its sides increase and the eroding streams have greater power; so that the rate of waste of a mountain depends upon its height. There are other considerations

which affect the matter, and the controlling conditions are somewhat complex, but it is true in a general way that as mountain masses grow the rate of waste increases much more rapidly than the altitude. It was hence argued most cogently by Powell that all large mountains are young mountains, and from the point of view of the uniformitarian, it is equally evident that all large mountains must be growing mountains; for if the process of growth is continuous and if a high mountain melts with exceptional rapidity before the play of the elements, it is illogical to suppose that the uprising of any mountain which to-day is lofty has to-day ceased. If, therefore, it were possible to ask of all great mountains the question whether they are now growing, and obtain an answer, a solution might be reached of the problem which has divided investigators; and for this reason great interest attaches to any answer which can be obtained in the case of any mountain. We shall presently see that the lake vestiges help us to an answer with regard to some of the mountains of Utah.

The origin of continents is closely allied to that of mountains. It is known by the same sort of geologic evidence that every part of every continent has been at some time submerged beneath the ocean, and that some parts have been many times submerged, and it has been established with equal certainty that at least some parts of the ocean have in the ages of the past been continental. The submergence of the land now continental has not been equable in all parts, but some districts were flooded while others were uncovered, and *vice versa*. Those districts which are at any time submerged are then subject to sedimentation, and those which stand as land surfaces are more or less degraded by erosion; but erosion and sedimentation both have their limits at sea level, and have no power either to build the sea bottom into land or to submerge the land. All the great changes have been produced by earth movements of uprising and depression, and must be referred to the action of subterranean forces either similar to or identical with those which have produced mountains.

With reference to the rate of continental movements, there is not the same conflict of opinion as concerning the growth of mountains, but they are generally regarded as slow and continuous. And there are none to question the fact that there have been notable local changes in the height of the land since the close of the Glacial Epoch and even some measurable changes within historic time. The evidence by which these movements are known has been derived almost exclusively from the vicinity of the ocean, but there are a few inland localities which afford facilities for their determination. The basin of Lake Bonneville is one of those localities.

Each shoreline of the old lake was originally the tracing of a level surface and was therefore horizontal. If it is not horizontal now, orographic movement must have intervened, and the difference of level between any two points of the same shore measures exactly the differen-

tial movements of the two points. It is, of course, conceivable, and it is indeed far from being improbable, that the entire basin has bodily moved upward or downward in the same interval of time, but of such changes the shorelines can give no proof; their evidence is limited to the relative vertical movements of different parts.

The value of the shorelines as an orographic record was early appreciated, and great pains were taken, not only during the past summer but at every opportunity in previous years, to ascertain by the aid of the spirit level the altitudes of the Bonneville and Provo shores at as many points as possible. The numerous railroad surveys which now intersect the region made it possible by running short accessory lines of leveling to compare together widely separated portions of the coast, and still other comparisons were made by running levels from the water surface of Great Salt Lake at various points of its margin to the ancient water margins upon contiguous mountain slopes. Where the use of the level was impracticable recourse was had to the barometer, and although its determinations are far less trustworthy they were made with such precautions and under such restrictions that the additional information they convey cannot be regarded as entirely valueless. The summer's work increased the number of determinations of the Bonneville shoreline by spirit level to seventeen, and of the Provo shoreline to nine. In localities where no means were available for the determination of the absolute height of the water marks, it was nevertheless frequently possible to ascertain the relative altitudes of the different shores, and this was repeatedly done; so that the difference of altitude of the Bonneville and Provo shorelines is somewhat more widely known than the absolute altitude of either.

The general results of the investigation are, first, that neither of the two shorelines is now horizontal, and, second, that the two are not parallel; whence it is evident that the region has been the scene of orographic movements both during the existence of the last high stage of the water and since the final subsidence. The detailed results are not so simply stated, but they are too interesting and instructive to be passed in silence.

At the time of its formation every part of the Bonneville shoreline (for example) fell within the same horizontal plane, and we may conceive that plane as extending indefinitely not only through the mountains beyond the water margin but over the valleys filled by the water, and as having a fixed relation to the bottom at every point. Every orographic movement which took place subsequent to the formation of the shoreline would have the effect of deforming this imaginary plane; and if we were able to determine at all points the present position of the plane we could draw a perfect picture of the deformation effected by subterranean forces in the given interval of time. The only portion of the plane, however, which can now be determined is that marked by the shoreline, and our knowledge of the deformation cannot therefore be perfect. Nevertheless, the ancient lake had so sinuous a shore,

and its surface was so frequently interrupted by islands, that a highly instructive restoration of the deformed plane could be made if only we knew the present height of every part of the shoreline; and even from the imperfect data which have been gathered it has been practicable to obtain a rude idea of the general character of the displacement.

If an outline of the lake be traced on a map, and if all points of the old shoreline which have now the same altitude be connected by a line, it is evident that this line will constitute a contour* of the surface of deformation. It is further evident that if a number of such lines be drawn, each at a different height, and if their several heights be chosen so as to form a uniform series, the lines will constitute a contour map of the deformed surface. An attempt was made to do this.

Three maps of the lake were prepared, and upon them the data were plotted. On the first every locality at which the height of the Bonneville shoreline had been determined was marked by writing the figures which express, in feet, the altitude of the shoreline at that point above the water surface of Great Salt Lake; on the second the determined heights of the Provo shoreline were similarly plotted; and on the third the determined differences of height between the two shorelines. The data on the first map illustrate changes which have occurred in the interval of time from the formation of the Bonneville shoreline to the present day; those on the second illustrate changes which have taken place between the formation of the Provo shoreline and the present day; and those on the third illustrate changes occurring after the formation of the Bonneville shoreline but before the completion of the Provo. When it was attempted to draw contour lines through and among the determined points of the third chart, it was found that the data were so irregular that they could be satisfied by no simple system of contours, and of the numerous complex systems which could be invented in conformity with them there was no single one entitled to preference. The result was therefore indeterminate. The chart of the post-Provo deformation proved more tractable, and all of its data were found to consist well with a simple system of contours drawn at vertical intervals of 25 feet. The post-Bonneville chart, which in the presence of full data should represent the combined result of the other two, was found to hold an intermediate position in facility of interpretation, admitting of a scheme of contours with vertical intervals of 100 feet. The post-Bonneville and post-Provo charts are reproduced in Plates XLII and XLIII.

* A contour is a device for the expression of topographic forms. Conceive a hill to be intersected by a horizontal plane; the line in which the plane meets the surface of the hill is a contour of the surface, and has everywhere the same height. If there are many intersecting planes parallel to each other and separated each from each by the same space, the corresponding contours constitute a system. It is evident that where the slope is steep, contours will fall near together, in a horizontal sense, and where it is gradual they will fall farther apart. When the contours of a hill are traced on paper they constitute a contour map. In practice the lines are not drawn on the ground, but on paper only, as a means of expressing the form of the ground.

Referring to Plate XLII it will be seen that the figure of deformation of the Bonneville shoreline exhibits at the north, in the district of the main body of the lake, an axis of uplift, coinciding approximately with the 113th meridian. The altitudes determined at Promontory and near Grantsville, points which lie slightly to the east of that meridian, are greater by about 100 feet than those along the eastern and western shores of the old lake. The westward slope of the anticline was demonstrated by a single station only, that near the town of Tecoma, and was not traced farther south, but the eastward slope was traced continuously southward along the eastern shore of the old lake quite to its southern end. At the extreme southern limit of the lake, the southwestern shore of Escalante Bay, there is a rapid rise of the surface of deformation toward the west, amounting to 200 feet in a distance of about twenty-five miles. In the northern part of the lake the range of altitudes, all of which were determined by spirit level, is 168 feet. At the south, where a portion of the altitudes were determined by the aid of the barometer, the range is 353 feet.

Plate XLIII exhibits in the same manner the curves of deformation of the Provo surface and the data from which they were drawn. At the Provo level the lake did not extend so far south as the Escalante Bay, and no verification is afforded of the indications there given by the Bonneville shoreline, but at the north the lines curve in a precisely similar manner about an axis in the vicinity of the 113th meridian. The greatest determined altitude of the Provo shoreline above Great Salt Lake is 680 feet, at the north end of the Aqui Mountains, near Grantsville, and the least determined height is 553 feet, at a point known as White Mountain, near the town of Fillmore; the difference between these two, or the range of all the determinations, is 127 feet.

The principal concurrent result of the two systems of measurement—that a region in the middle of the main body of the ancient lake has in recent times been upraised with reference to the adjacent region at the east—finds a curious and interesting support in an entirely independent fact. Great Salt Lake does not occupy a marked local depression but rests upon the surface of a broad plain. Its mean depth is scarcely fifteen feet, and only a slight oscillatory movement of the plain would be necessary to decant its water into another portion. By reverting to the map in Plate XLIII, the reader may obtain a clear idea of the form of this plain and of the position of the lake upon it. He will see also that the Bear River, the Weber, and the Provo, the only large streams which send their water to the plain, all rise to the eastward and enter it from the east side. That is the side of the Wasatch Mountains and associated uplands, which in the time of Lake Bonneville as well as now afforded the chief and almost exclusive water supply of the basin. The sediment which accumulates in the basin is brought to it by the tributary water, and the greater part of it is conveyed by these large streams flowing from the east. If there were no disturbing

causes it is easy to see that the detritus would build up the eastern side of the plain and leave the greatest depression at the west. The normal position of Great Salt Lake is therefore in the extreme western part of the basin, between meridians 113 and 114, and its actual position between meridians 112 and 113 must be regarded as abnormal. To account for it there is no hypothesis so simple and satisfactory as that which assumes an orographic tilt of the surface of the plain—a tilt executed at a rate sufficient to overcome the opposing tendency of the silt-bearing streams from the east. The position of the lake therefore conspires with the indication of the deformed ancient lake margins to show that the region of the eastern margin of Lake Bonneville has recently undergone depression and presumably is still subsiding.

The gentle undulations of the earth's crust which are thus exhibited are of the order of those which have produced continents and have continuously modified their contours and limits. Indeed Great Salt Lake is in some sense an epitome of the ocean, and its position within its basin is as thoroughly controlled by orographic displacement as are the greater features of the distribution of land and water upon the surface of the globe.

When these movements are spoken of as "orographic" it must not be understood that they are here concerned in the construction of mountains. The greatest mountain of the district, and the one therefore to which the uniformitarian would look for evidence of recent growth, is the Wasatch, a massive range which forms the eastern wall of the desert. The deformation indicated by the shorelines actually diminished its altitude with reference to parallel and smaller ranges at the west, instead of increasing it, and therefore tended to make it a less conspicuous structure than before. There were, however, other changes in progress, and these, as we shall see, had the effect of really increasing the height of the Wasatch above its base.

It should be said in passing that the only growth of a mountain with which we are here concerned is growth as referred to the adjacent country. It is hardly conceivable that it should ever be known whether the summit of a mountain is at one time nearer the center of the earth than at another, and it is a matter of great difficulty to determine the relation in altitude which a mountain summit bears to our least variable datum plane, the level of the ocean. And even if these relations were known they would not determine the height of a mountain *as a mountain*, because no eminence, however great, would constitute a mountain unless surrounded by land of less altitude. In discussing the growth of a mountain, therefore, we are concerned only with the relation of its crest or its mass to the adjacent lowlands, and we must regard it as actually growing so long as its height increases relatively to the lowlands.

In order to understand the evidence of the recent growth of the Wasatch it is necessary to understand its general structure. In detail its

structure, like that of most mountains, is highly complex, but its dominating feature admits of easy statement. Before the mountain rose its site was occupied by horizontal strata. The uplifting by which it was produced had the effect of bending these strata upon one side, but broke them off upon the other, so that at the east the superficial strata of the country are seen to turn up toward the flanks of the range, while no such phenomena appear at the west. The diagram will probably convey the idea more clearly than words. At A are represented the horizontal strata from which the rocks of the mountain were torn away. At B the dissevered prolongations of the same strata appear in an upturned position. If there had been no erosion during the uplifting of the mountain it would be much higher than it actually is, and the crest would have some such position as that indicated by the dotted line. But erosion has actually supervened, and a large share of the uplifted mass represented by C has been worn away and deposited upon the flanks of the range in the strata D and E. Approaching the mountain from the

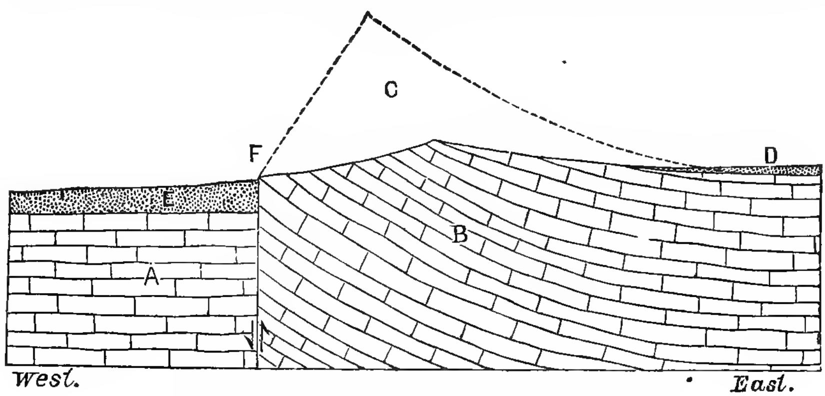


FIG. 21.—Generalized Cross-section of the Wasatch Range.

west one traverses the surface of the deposit E, which is made up entirely of fragments from the range, and at the point F passes abruptly onto solid rock—the worn edges of the upturned strata. He crosses there the line produced by the intersection of the fault plane with the surface of the ground, and this line is everywhere marked at the present day by an escarpment or sudden ascent, produced by the last slipping of the rocks along the fault plane.

Mountain structures of this sort are not infrequent in the Great Basin, and it is by no means rare that a definite escarpment is found at the base of a range, recording a faulting at so recent a date that its evidence has not been obliterated by erosion, but there is usually no manner of fixing the date of the last movement with any high degree of precision. In the case of the Wasatch, however, our information is concise. The slopes interrupted by the escarpment are not simple alluvial slopes or rock slopes carved by subaerial agencies, but are slopes characterized by the peculiar sculpture of the waves; and the phenomena show not

only that the last uplift of the Wasatch took place after the formation of the Bonneville and Provo shores, but that the water of Great Salt Lake has not since been even fifty feet higher than it is at present. It is therefore demonstrated that an actual uplift of the mountain occurred at so recent a date as to leave no reasonable suspicion that its growth has now ceased.

The amount of displacement along this fault plane is not great, but it is probably greater than the amount of coincident erosion of the mountain top; so that it is reasonable to believe that the Wasatch is a greater mountain now than it was during the existence of the Bonneville Lake. Where the range is highest the amount of recent faulting at its base is from fifty feet to seventy-five feet, and it diminishes irregularly in either direction—the fault being traceable from the town of Willard at the north to that of Levan at the south, a distance of one hundred and thirty-five miles.

SUMMARY.

In brief, the work of the year may be said to have completed the demonstration of the following conclusions:

1. The climatic episode of which Lake Bonneville was the expression consisted of two humid maxima, separated by an interval of extreme aridity. The second maximum was the more pronounced; the first the longer.
2. The time elapsed since the close of the Bonneville epoch has been briefer than the epoch, and the two together are incomparably briefer than such a geologic period as the Tertiary.
3. The period of volcanic activity in the Great Basin, which covered a large share of Tertiary time, continued through the Quaternary also, and presumably has not yet ended.
4. Such earth movements as are concerned in the molding of continents had not ceased in Western Utah at the close of the Bonneville Epoch, and presumably have not yet ceased.
5. The Wasatch Range, the greatest mountain mass of Utah, has recently increased in height, and presumably is still growing.